

Galaxy Deconstruction: Clues from Globular Clusters

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Abstract. The present-day globular cluster populations of galaxies reflect the cumulative effects of billions of years of galaxy evolution via such processes as mergers, tidal stripping, accretion, and in some cases the partial or even complete destruction of other galaxies. If large galaxies have grown by consuming their smaller neighbors, or by accreting material stripped from other galaxies, then their observed globular cluster systems are an amalgamation of the globular cluster systems of their progenitors. Careful analysis of the globular cluster populations of galaxies can thus allow astronomers to reconstruct their dynamical histories.

1. Introduction

The origin of galaxies is one of the great outstanding problems in modern astrophysics. How and when did galaxies form? How have they evolved over time? How does environment influence their properties?

One way to unravel the secrets of galaxy formation is by studying their globular cluster populations. Most galaxies possess globular cluster systems of various richness, ranging from dwarf galaxies with only a handful of globulars, to supergiant elliptical galaxies with tens of thousands of globulars surrounding them (see Harris 1991 or van den Bergh 2000 for reviews). Because globular clusters are among the oldest stellar ensembles in the universe, they can provide important clues about the formation of their parent galaxies.

The earliest studies of globular clusters were, by necessity, limited to our own Galaxy and its nearest neighbors. Over the past few decades, however, there has been tremendous progress in our understanding of globular cluster systems of other galaxies. One of the most important recent discoveries in the study of extragalactic globular cluster systems is that most large galaxies appear to possess two or more chemically distinct globular cluster populations (e.g., Gebhardt & Kissler-Patig 1999; Forbes & Forte 2000; Kundu & Whitmore 2001). Some examples are shown in Figure 1, where two peaks are seen in the distribution of globular cluster metallicities for clusters associated with four large elliptical galaxies.

A number of different theories have been proposed to explain the origin of these bimodal globular cluster metallicity distributions. An obvious way to

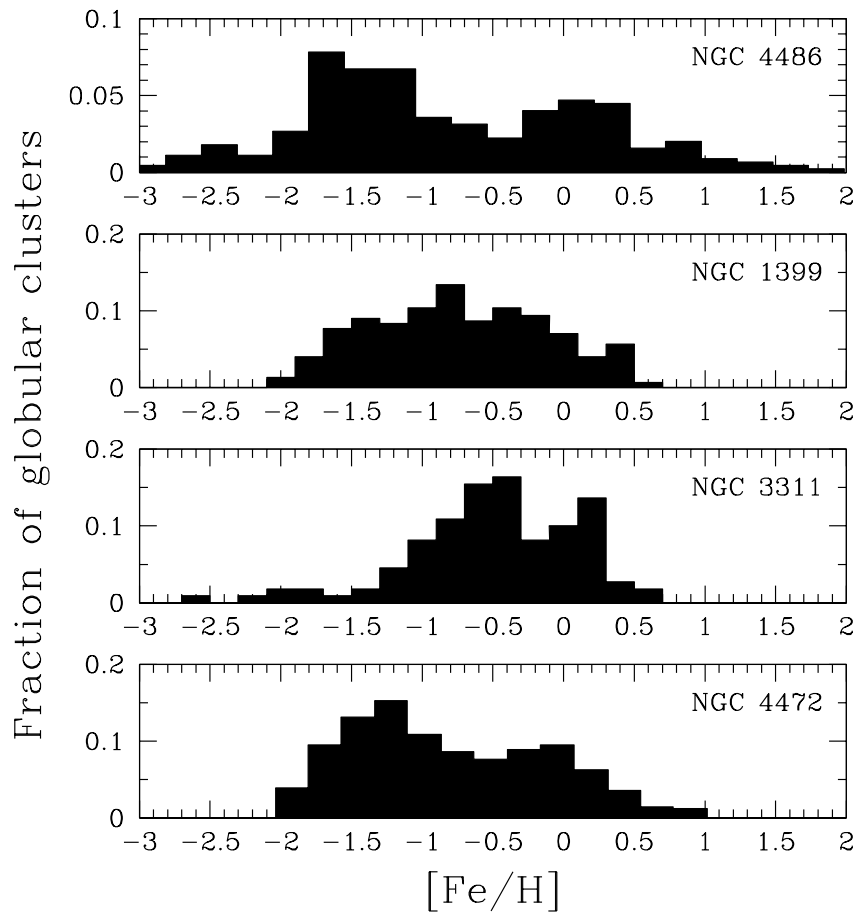


Figure 1. The observed metallicity distribution of globular cluster systems associated with four giant elliptical galaxies. Note the presence of two distinct peaks in most cases. The majority of large elliptical galaxies studied to date exhibit bimodal globular cluster metallicity distributions.

generate two or more chemically distinct globular cluster populations in galaxies would be through two or more bursts of globular cluster formation. This might occur, for example, if mergers of gas-rich galaxies trigger the formation of new globulars (Schweizer 1987; Ashman & Zepf 1992), resulting in the birth of multiple generations of globular clusters. Similarly, one might envision a multiphase galaxy collapse model in which the metal-poor globular clusters formed during the initial collapse of a protogalactic gas cloud, and the metal-rich globulars formed some time later (Forbes, Brodie & Grillmair 1997; Larsen et al. 2001). In both of these scenarios, the metal-poor globular clusters surrounding galaxies such as those shown in Figure 1 would be their original population that formed

from low-metallicity gas at early epochs, and the metal-rich globulars would have formed more recently from gas that was enriched by stellar evolution.

Alternatively, bimodal or multimodal globular cluster metallicity distributions could also arise quite naturally from galaxy mergers and/or accretion of globulars stripped from other galaxies *without needing to invoke the formation of multiple generations of globulars* (Côté, Marzke, & West 1998; Côté, Marzke, West & Minniti 2000). Motivation for this model came from a simple fact: for those elliptical galaxies that exhibit a bimodal globular cluster metallicity distribution, the metallicity of the metal-rich peak shows a clear correlation with parent galaxy luminosity, in the sense that the most luminous galaxies have the most metal-rich globulars (Forbes, Brodie & Grillmair 1997; Forbes & Forte 2001). However, no such correlation is seen for the metal-poor peak, it appears to be largely independent of parent galaxy luminosity. To my collaborators and I, this suggests that the *metal-rich* globular clusters are innate to large ellipticals, and the metal-poor ones were added later either through mergers or accretion.

2. Globular clusters as diagnostics of galaxy mergers

There is no doubt that galaxy mergers have occurred frequently throughout the history of the universe. Figure 2 shows an image of a supergiant elliptical galaxy in which the partially digested remains of several smaller galaxies are still clearly visible. Many large galaxies today may have grown to their present sizes by devouring smaller companions. If so, what becomes of the globular cluster populations of the galaxies that were consumed?

There is also evidence of ongoing galaxy destruction in rich clusters, and countless galaxies may have met their demise over a Hubble time (e.g., Gregg & West 1998; Calcanéo-Rodin et al. 2000). An example is shown in Figure 3. Because they are dense stellar systems, globular clusters are likely to survive the disruption of their parent galaxy, and will accumulate over time in the cores of rich galaxy clusters. The ongoing destruction of the moderate-sized elliptical galaxy shown in Figure 3, for example, will likely strew several hundred globulars into intergalactic space. Some of these may eventually be incorporated into other galaxies, a sort of recycling on cosmic scales (Muzzio 1987). In particular, giant elliptical galaxies at the centers of rich galaxy clusters, which are observed to have enormously rich globular cluster populations, may have inherited myriad intergalactic globular clusters (West et al. 1995).

If large galaxies have grown by consuming smaller neighbors or by accreting material torn from other galaxies, then their present-day globular cluster systems are an amalgamation of the globular cluster systems of their victims. Côté et al. (1998) and Côté et al. (2000) showed that the growth of large galaxies through mergers or accretion will invariably be accompanied by the capture of metal-poor globulars, resulting in bimodal (or even multi-modal) metallicity distributions that are strikingly similar to those seen in Figure 1.

Our prescription for building a large elliptical galaxy with a bimodal globular cluster metallicity distribution is remarkably simple:

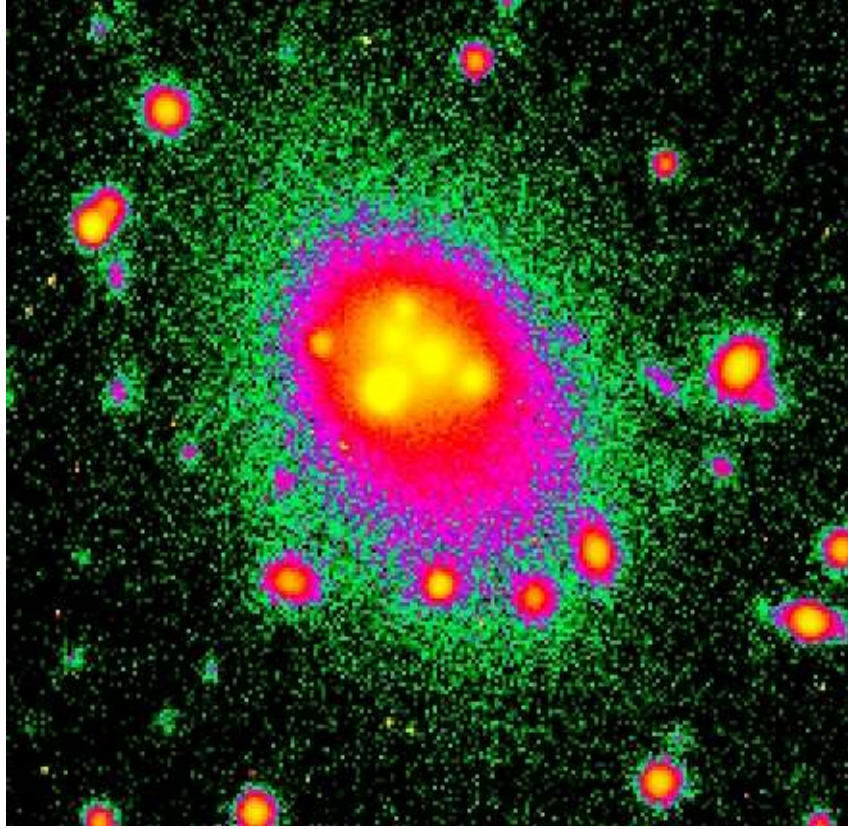


Figure 2. The brightest elliptical galaxy in the cluster Abell 3827. Several smaller cannibalized galaxies are clearly evident in the central regions. Globular clusters belonging to these galaxies are likely to survive the eventual disruption of their parent galaxies, and thus will become part of this giant elliptical. If most large elliptical galaxies have grown by cannibalizing smaller neighbors, then their globular cluster populations today are composite systems that can provide information about the progenitor galaxies.

- We assume that galaxies obey a Schechter-like luminosity function, as is observed. This sets the relative numbers of galaxies of different luminosities that are available for merging.
- We assume that each galaxy is born with its own intrinsic globular cluster population, and that the number of globulars per unit galaxy luminosity is constant, which is consistent with observations (Harris 1991). This

determines how many globular clusters each galaxy has available to donate during mergers.

- We assume, again from observations, that the mean metallicity of a galaxy's original globular cluster population increases monotonically with parent galaxy luminosity (Côté et al. 1998). Smaller galaxies have metal-poorer globulars on average than larger galaxies.

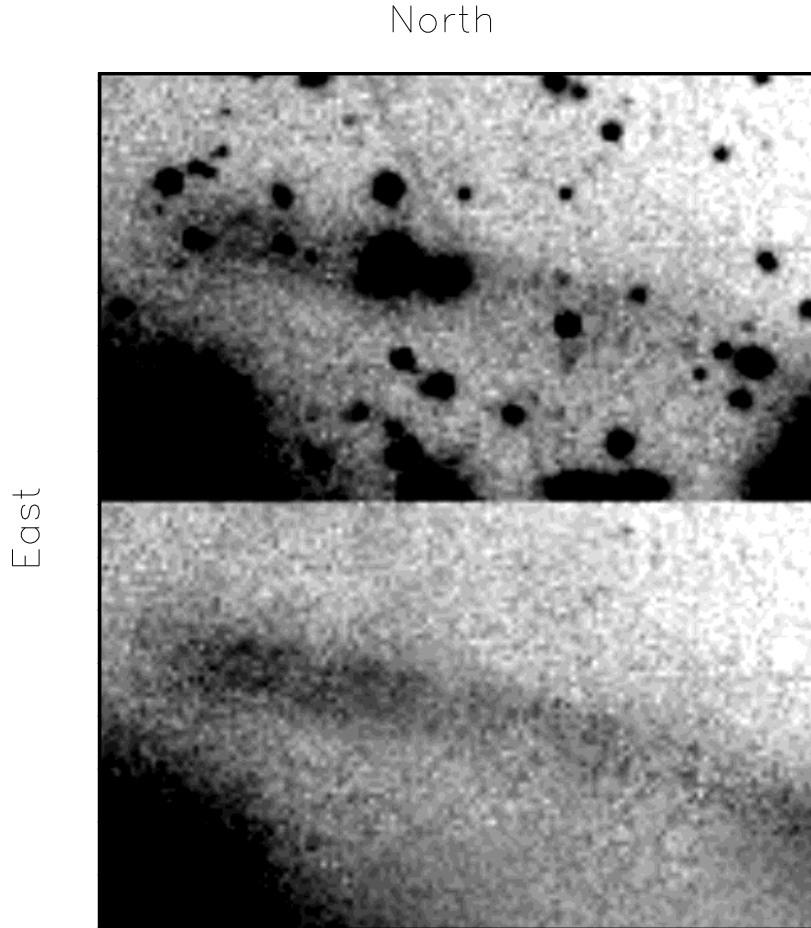


Figure 3. A tidally disrupted galaxy in the Coma cluster (from Gregg & West 1998). The top panel shows the raw image, and the bottom panel has been cleaned of foreground objects to highlight the ~ 150 kpc long plume of material. The partial, or in some cases complete, disruption of galaxies in dense environments will create a population of intergalactic stars and globular clusters. These freely roaming globulars may be accreted later by other galaxies.

Beginning with a medium-sized elliptical galaxy as a seed, we allow it to consume its smaller neighbors at random, stopping after enough mergers have occurred to yield a large elliptical. We assume that globular cluster numbers are conserved during mergers, so the larger galaxy gains the globulars from the smaller galaxies that it consumed.

Figure 4 shows some results of Monte Carlo simulations based on the Côté et al. (1998, 2000) model. Our simulations indicate that 80 to 90% of large elliptical galaxies formed in this way exhibit bimodal (or in some cases multimodal) globular cluster distributions. The locations of the metal-rich and metal-poor peaks also agree well with observations (compare Figures 1 and 4). In our model,

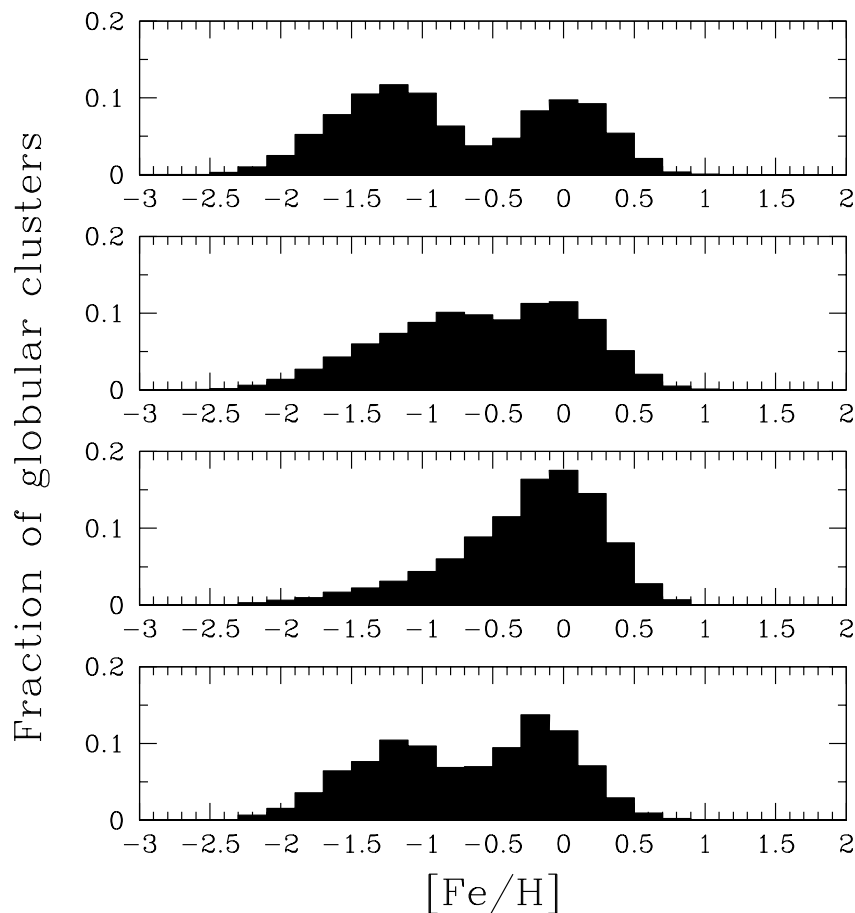


Figure 4. Results from some simulations based on the dissipationless merger model of Côté, Marzke & West (1998). These simulations show that bimodal globular cluster metallicity distributions are easily produced by dissipationless galaxy mergers and accretion, without needing to posit the formation of multiple bursts of globular cluster formation.

the metal-rich globular clusters of large ellipticals belonged to the progenitor galaxy seed, and the metal-poor globulars were inherited from the many smaller galaxies that it consumed during its growth, or by accretion of intergalactic globulars that were torn from other galaxies. The globulars gained from mergers or accretion are predominantly metal-poor because they originate mostly in low-mass galaxies.

It is noteworthy that unimodal globular cluster metallicity distributions also occur from time to time in our model. An example can be seen in Figure 4. This is not surprising, given the stochastic nature of the merger process. For instance, a large elliptical could in principle be built by merging many small dwarf galaxies (resulting in the globular cluster metallicity distribution of the final merger remnant exhibiting a single metal-poor peak), or by merging two or three medium-sized galaxies (which might lead to a single metal-rich peak), or by merging galaxies over a wide range of luminosities (which yields bimodal or multimodal globular cluster metallicity distributions).

Unfortunately, our model seems to often be misunderstood or misrepresented in the literature. For example, claims that the Côté et al. (1998, 2000) model is ruled out by the discovery of bimodality in some low-luminosity ellipticals (e.g., Forte et al. 2001; Kundu & Whitmore 2001) are completely unfounded; Côté et al. (2000) demonstrated that it is quite straightforward to reproduce the bimodal globular cluster metallicity distribution of our own Galactic spheroid (which has $M_V \simeq -19.9$) as a consequence of accretion and mergers, and hence the same should be true for intermediate- and low-luminosity elliptical galaxies. Similarly, recent assertions that the location of the metal-poor globular cluster peak also correlates weakly with parent galaxy luminosity is *not* “hard to explain within the accretion/merger pictures” (Larsen et al. 2001). A careful reading of the original Côté, West & Marzke (1998) paper would show that in fact we predict this very result; see Section 3.1.2 of that paper, which states “there is a slight tendency for the brighter gE’s to capture globular cluster populations that are more metal-rich than those accreted by their fainter counterparts (since the brighter gE’s are able to accommodate the capture of more luminous intruder galaxies).”

If our model is correct, then it offers the exciting possibility of placing some quantitative constraints on the number and types of mergers that galaxies have experienced over their lifetimes by comparing the relative numbers of metal-rich and metal-poor globulars that they possess. Côté et al. (1998) used this reasoning to conclude that M49, the most luminous elliptical galaxy in the Virgo cluster, must have gained roughly 2/3 of its present luminosity by consuming other smaller Virgo galaxies. More recently, we have applied these same techniques to understanding the formation of our own Milky Way galaxy. Côté et al. (2000) showed that the present-day globular cluster system of the Milky Way strongly suggests that the Galaxy’s spheroid was assembled from a large number of metal-poor protogalactic fragments. Hence even a relatively low luminosity system like the Milky Way spheroid can and does possess a bimodal distribution of globular cluster metallicities.

3. Where do we go from here?

Clearly the competing theories for the origin of bimodal globular cluster metallicity distributions make quite different predictions regarding the ages of globulars. If the metal-poor and metal-rich globulars surrounding large elliptical galaxies are the result of multiple bursts of cluster formation, then the two populations should have quite different ages. If, on the other hand, bimodal metallicity distributions can be explained by dissipationless merging as described above, then the metal-poor and metal-rich globulars should all be old.

Recently, Beasley et al. (2000) measured ages and metallicities of globular clusters in M49, and concluded that (within the sizeable uncertainties) the metal-poor and metal-rich populations are coeval and old. This clearly seems to support the Côté et al. (1998, 2000) picture. However, more precise data are needed to reduce the uncertainties before firm conclusions can be drawn. With that goal, we have obtained *Hubble Space Telescope* observations of $\sim 10^3$ globular clusters associated with the giant elliptical galaxy M87 in order to accurately determine their ages using a powerful narrow-band photometry technique.

The hypothesis that galaxies might accrete substantial numbers of intergalactic globular clusters also needs to be tested with direct observations of these objects to determine if they really exist and in what numbers. Unlike many theories for the origin of globular cluster populations, the intergalactic globulars hypothesis is easily falsifiable; if a significant population of intergalactic globulars is not detected in the cores of galaxy clusters, then this idea will have to be abandoned. My collaborators and I are currently analyzing *HST*, Keck, Subaru and CFHT images that we obtained to search for intergalactic globulars in the Virgo, Coma and Abell 1185 galaxy clusters.

There is also work to be done on the theoretical front. The simple merger model described here is admittedly somewhat naive. For example, we assumed equal merger probabilities for all galaxies, when in reality there is likely to be some mass dependence of merging. As a step towards more realistic models, Frazer Pearce and I are collaborating in a study of the merger histories of galaxies that form in very high-resolution N-body cosmological simulations. By following the detailed merger histories of galaxies from high redshifts to the present, and inputting simple models of globular cluster formation at different epochs, we will be able to make quantitative predictions regarding the evolution of globular cluster metallicity distributions in galaxies as a function of time.

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Discussion

Michael Rich: I support your view; in fact, in the Milky Way there are old metal-rich globular clusters in the bulge and, as I mentioned in my talk, when you age-date them they seem to be rather old – at least of order 13Gyr. We have a white dwarf distance modulus distance to 47 Tuc which gives a 13Gyr age, and then we can compare 6528 and 6553 to that, and we think that these red globular clusters were formed along with the Galactic bulge, very early in the history of the Galaxy. So I think that red cluster systems have to do with the formation of the bulge. Now, is the bulge formed in a merger event? Maybe, the simulations show these very early mergers. On the other hand, black hole mass is correlated with bulge velocity dispersion and black holes are very early galaxy formation events. So I don't know, but I would tend to support the view that the red clusters were formed in the metal-rich spheroid.

West: Thanks. Pat Côté, Ron Marke, Dante Minniti and I published a paper just last year in which we showed that one can account for the properties of the Milky Way spheroid and its globular cluster system if it consumed upwards of 10^3 little dwarf galaxies during its formation.

Hugh Harris: The clusters are usually found more widely distributed spatially than the halo light in their galaxy. How do you interpret that?

West: We think that accretion, not just mergers, has probably played an important role by stripping globular clusters from some galaxies and then adding these to the outer regions of others, especially giant ellipticals in the centers of rich clusters. This would explain why some of large ellipticals, like M87 for example, have far more globulars per unit galaxy luminosity than expected, and why they have very extended distributions.

Alan Stockton: The problem with making large bulges or large ellipticals from a lot of small things, of course, is the luminosity-color relation, or luminosity-metallicity relation. So you indicated in most cases you favor starting with a fairly large progenitor and then putting a bunch of small things on it. Do you still run into any problem with the observed dispersion in that relation?

West: One can imagine making a large elliptical in many different ways, either from the merger of many small dwarfs, in which case the elliptical should be pretty blue as well, or from a number of bigger progenitors which would have had redder colors. The existence of the observed luminosity-color relation for galaxies suggests that in most cases large ellipticals can't have formed just from the merger of many dwarfs – that probably wouldn't work, you're right. It suggests that most large ellipticals must have started from fairly large progenitor seeds. As this seed galaxy consumes smaller neighbors, this will dilute the luminosity-color relation, but won't necessarily obliterate it.